COMPUTATIONAL SIMULATION OF THE LOW CHROMOSPHERE HEATING BY THE SHOCK WAVES' SERIES

S.V. Alekseenko[1], G.I. Dudnikova[2], V.A. Romanov[3], D.V. Romanov[4], and K.V. Romanov[4]

[1] Institute of Thermophysics SB RAS, 630090 Novosibirsk, Russia
[2] Institute of Computational Technologies SB RAS, 630090 Novosibirsk, Russia
[3] Krasnoyarsk State Academy of the Non-ferrous Metals and Gold,660049 Krasnoyarsk, Russia
[4] Krasnoyarsk State Commercial Institute, 660049 Krasnoyarsk, Russia

1. Introduction

The low chromosphere's heating by the series of shock waves is investigated. Waves are initially generated in the solar photosphere. Due to propagation in the strong stratified solar atmosphere the waves are overturning to the shock waves. The goal of present paper is to investigate it using 2D approximation.

To describe the solar atmosphere one-fluid hydrodynamics with taken into consideration radiative heat transfer and absence of the thermodynamic equilibrium is used. Computer modeling is performed for one- and two-dimensional formulation of problem. The results obtained are important for understanding the physics of star atmospheres' reaction on the dynamical disturbances like flares, mass surges and heating by penetrating convection.

2. Model approximation

Solar atmosphere is mixed hydrogen-helium plasma in strong gravitational field (for exact chemical compositions see [1]). The hydrodynamic approximation is proved to be valid due to smallness of particle's free path compared with characteristic spatial scale of the atmosphere (scale of height $\Lambda = p/(\rho g) = \left(d\ln(p)/d\,r\right)^{-1}$) and smallness of typical time of the kinetic processes (like ionization, recombination, collision rate and so on) compared with time scale of the investigated processes. Thermoconductivity should be taken into consideration because thermoconductivity coefficient depends only on temperature and thermoconductivity becomes important in the chromosphere's upper layer, where energy's volume density becomes small due to a strong stratification. Instead of thermoconductivity, viscosity is negligible in all bulk of photosphere and chromosphere.

The radiative transfer is the most important source of energy loss in solar atmosphere. Photon's free path even in the middle chromosphere significantly exceeds the height's scale, so typical value of optical density is infinitesimal. Optical density becomes comparable with unity only in the photosphere and it proves the using of volumetric loss approximation for radiative transfer describing [2, 3 and4].

Solar atmosphere is not in thermodynamic equilibrium (TE), so ions' and electrons' densities, absorption factor and emittance are founded by solving the system of kinetic equations included the all significant kinds of ionisation and recombination processes. The main ionization process is ionization by the electron-atom collision, and main recombination process is free-bound recombination instead of reversal process of the tree body recombination. That kind of equilibrium is typical for stellar atmospheres and named as *corona equilibrium*. The densities of ions, electrons and neutral atoms for solar chromosphere are founded in [2, 3] as

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
23 Aug 2002	N/A	-

Title and Subtitle Computational Simulation of the Low Chromosphere Heating by the Shock Waves Series	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Institute of Theoretical and Applied Mechanics Institutskaya 4/1 Novosibirsk 530090 Russia	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) EOARD PSC 802 Box 14 FPO 09499-0014	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes See also ADM001433, Conference held International Conference on Methods of Aerophysical Research (11th) Held in Novosibirsk, Russia on 1-7 Jul 2002	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 5	

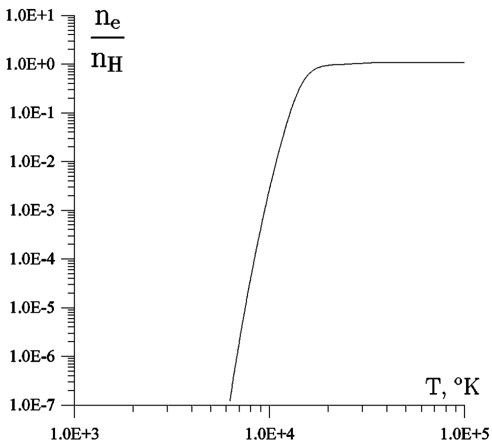

Figure 1. Dependence of ionization parameter on temperature.

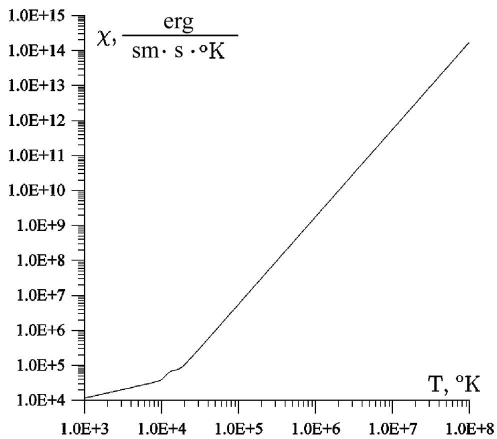

Figure 2. Dependence of heat conductivity coefficient on temperature

well, as volumetric loss power per volume unit. (Rosseland opacities (absorption factor, averaged over spectra) usually are founded in case of thermodynamic equilibrium [5, references herein]. They are useless because of the correlation between absorption factor and emittance is consequence of thermodynamic equilibrium [6]).

So a two-dimensional system of equations which describes the solar atmosphere's plasma in hydrodynamic approximation with radiative heat transfer and thermoconductivity considered is:

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ w\end{pmatrix}+\frac{\partial}{\partial x}\begin{pmatrix}\rho u\\ p+\rho u^2\\ \rho uv\\ u\cdot(p+w)-\chi\cdot\dfrac{\partial T}{\partial x}\end{pmatrix}+\frac{\partial}{\partial y}\begin{pmatrix}\rho v\\ \rho uv\\ p+\rho v^2\\ v\cdot(p+w)-\chi\cdot\dfrac{\partial T}{\partial y}\end{pmatrix}=\begin{pmatrix}0\\ \rho g\\ 0\\ \rho ug-P_{rad}\end{pmatrix}.$$

Here ρ designates plasmas density, p and $\varepsilon = p/((\gamma-1)\cdot\rho)$ – denote pressure and mass density of plasma internal energy, $w=\rho\varepsilon+\rho(u^2+v^2)/2$, u, v – components of speed, $g = 274\ m/s^2$ – acceleration of gravity (x axis is antiparallel to the g vector), $\chi=\chi(T)$ – coefficient of thermoconductivity, $P_{rad}(\rho,T)$ – volumetric loss power caused by emittance (founded in [2 - 4]: $P_{rad}(\rho,T)=n_e n_H\cdot L_r(T)$). In case of corona equilibrium $n_e=\alpha(T)\cdot n_H$, so volumetric loss power is proportional to the plasma density raised to the second power. Functions $\chi(T),\alpha(T),P_{rad}(\rho,T)/(n_e n_H)$ are plotted on Figs. 1–3.

The system of equations is solved in rectangular area. On an axis "y" the periodic boundary conditions are set. On a low bound the speed sets as a function from time and coordinate (simulating a source of acoustic waves). On a upper bound the boundary condition of waves' issue is putted. All equations are dimensionless and the units of physical parameters are listed below:

$[r] = 10^7$ cm	$[t] = 10^{1,5}$ s	$[u] = [r]/[t]$	$[\rho] = 10^{-6}$ gr/cm^3
$[T] = 10^4$ K	$[p] = 10^5$ erg/cm^3	$[\varepsilon] = 10^{11}$ erg/gr	$[g] = [u]^2/[t]$

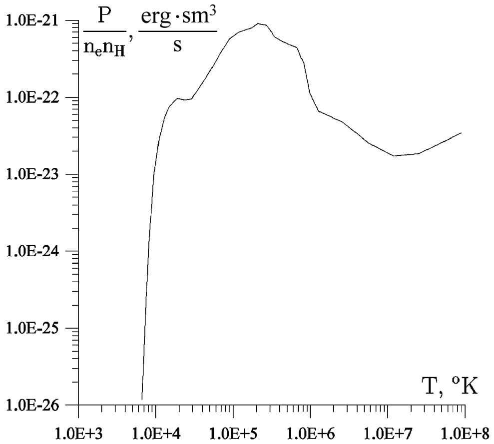

Figure 3. Dependence of volumetric losses power on temperature.

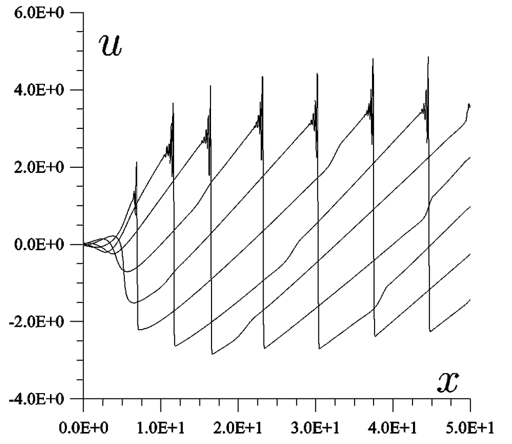

Figure 4. Speed distributions over height for several times for one-dimensional heating (units are dimensionless).

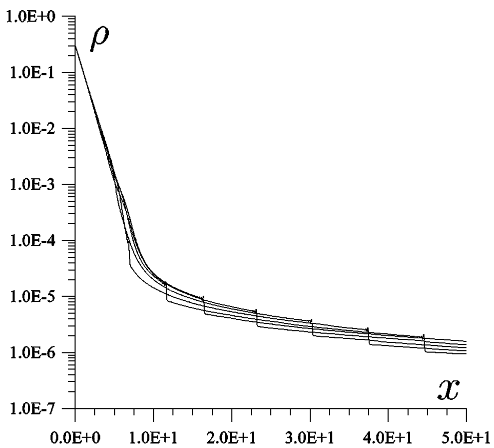

Figure 5. Density distributions over height for several times for one-dimensional heating (units are dimensionless)

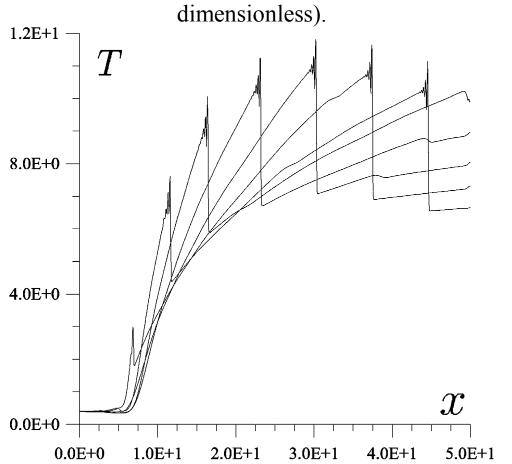

Figure 6. Temperature distributions over height for several times for one-dimensional heating (units are dimensionless)

3. Atmosphere's heating by the series of acoustic waves

Earlier the atmosphere's heating was investigated in one-dimensional formulations of a problem and numerical scheme's realization together with model's approximations force the height's range to be less than 2500 km [7, 8]. The solar atmosphere is hardly inhomogeneous in all directions, so the research of a problem at least in two-dimensional formulation is of strong interest.

With the purpose to find out influence of spatial inhomogeneity on atmosphere's heating two formulations of problem are performed. In the first computer simulation the wave's source does not depend on "*y*" coordinate, so the formulation is one-dimensional. On the left boundary speed is set to $u(y,t) = u_0 \sin(\omega t)$, where $u_0 = 100\, m/s$, $2\pi/\omega = 100\, s$ are the typical parameters of acoustic waves in the solar photosphere [9]. Weak acoustic waves, initially generated on the low boundary, are propagating to the upper boundary, so waves' amplitude is exponentially increasing with height due to plasmas' stratification. If speed of flow becomes bigger

than sound speed, waves are turning into shock waves' series (Fig. 4). The result of heating by shock waves is a significant decreasing of height's scale (Fig. 5), so after 5-8 shock wave's transitions the atmosphere becomes quasi-stationary and heating by shock waves is compensated by radiation losses. When heating process relaxes to stationary state, the shock wave amplitude becomes of order $1.26 \cdot 10^6$ cm/s. Distribution of plasmas' parameters (for corresponding parameters of wave's source) are showed in Figs. 4, 5, and 6.

In the second computer simulation wave's source is inhomogeneous and his spatial scale is $\lambda = 5.0 \cdot 10^8$ *см*: $u(y,t) = u_0 \cdot \sin(\omega t) \cdot \sin(2\pi y/\lambda)$. The initial atmosphere was taken to be heated by homogeneous wave's source instead of be in isothermal hydrostatic equilibrium. Though the wave's source's scale is more than 100 times bigger than scale of height, influence of that inhomogeneity is sufficient. Shock waves get curved and their fronts' expansion reduces the increasing of wave's amplitude with height as well, as power of atmosphere heating. In domains upper than 15000 km shock wave develops into a strong curved arc, which vertical size is of order of scale height and horizontal size is 2-4 times greater than λ. It leads to elimination of waves' series regular structure and explains the absence of well-defined shock waves' series in the solar corona according to observational data. Minimal and maximal values of the some plasma flow parameters during period of wave's source is showed on figures 7-10. On figures 11, 12 typical distributions of the temperature and vertical component of speed are showed. Parameters u_0, ω are the same as for previous one-dimensional variant.

4. Conclusion

In present paper the solar atmosphere's heating is investigated using one-dimensional and two-dimensional formulation of the problem. It is proved that in strong stratified medium the influence of wave's source's inhomogeneity becomes important on heights, which are comparable with several scales of height instead of scale of source's inhomogeneity. Performed investigation limits the earlier obtained one-dimensional result's applicability to the domains with heights of order 700 – 1200 km, because of typical wave source scale is 700-1500 km (granule) or 3000 –7000 km (length of coherence of 5-min oscillations).

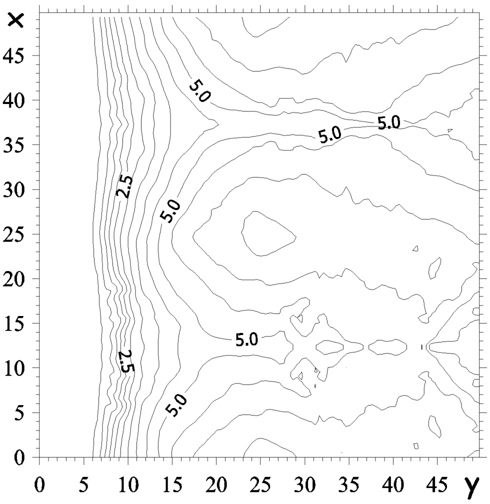

Figure 7. Minimal over period temperature for atmosphere, heated by non-uniform wave's source (units are dimensionless).

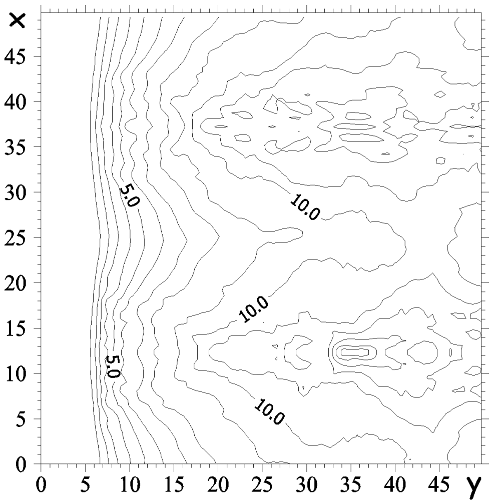

Figure 8. Maximal over period temperature for atmosphere, heated by non-uniform wave's source (units are dimensionless).

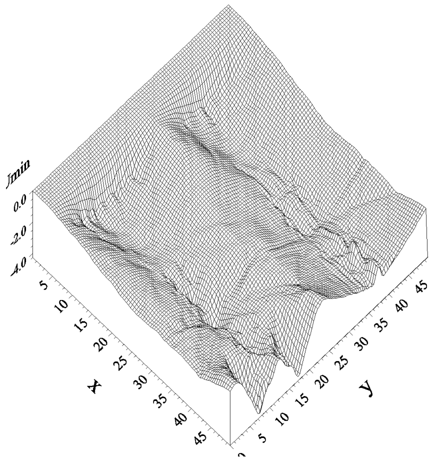

Figure 9. Minimal over period vertical speed's component for atmosphere, heated by non-uniform wave's source (units are dimensionless)

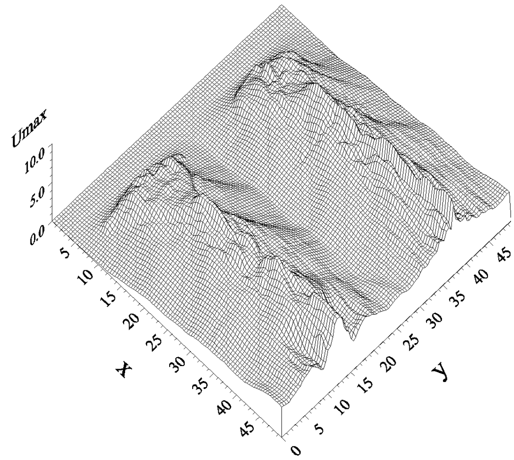

Figure 10. Maximal over period vertical speed's component for atmosphere, heated by non-uniform wave's source (units are dimensionless)

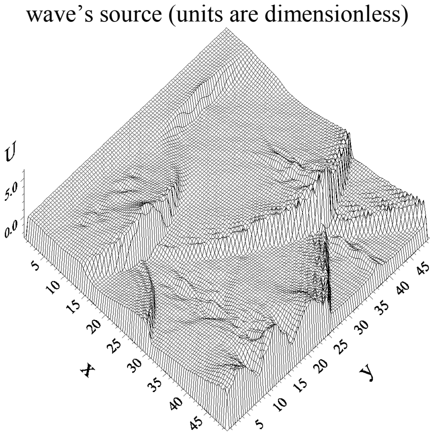

Figure 11. Spatial distribution of the vertical speed's component for the atmosphere, heated by non-uniform waves' source (all units are dimensionless)

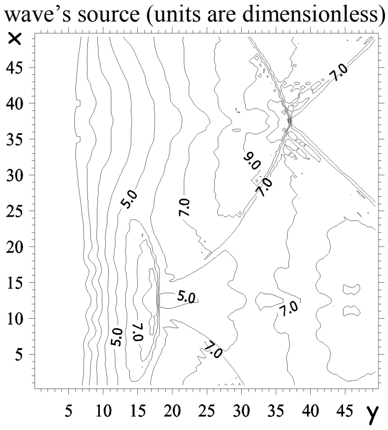

Figure 12. Spatial distribution of the temperature for the atmosphere, heated by non-uniform waves' source (all units are dimensionless)

REFERENCES

1. **Lang K.R.** Astrophysical formulae. Berlin, Heidelberg, New York: Springer-Verlag, 1974. (In Russian: Lang K. Astrophysical formulae. Moscow: Mir, 1978.)
2. **Cox D.P., Tucker W.H.** Ionization equilibrium and radiative cooling of a low-density plasma // Astrophysical J. 1969. Vol. 157. P.1157-1167.
3. **Cox D.P., Daltabuit E.** Radiative cooling of low-density plasma // Astrophysical J. 1971. Vol. 167. P. 113-117.
4. **McWhirter R.W.P., Thonemann P.C., Wilson R.** The heating of the Solar Corona: a model based on energy balance // Astronomy and Astrophysics. 1975. Vol. 40. P. 63-73.
5. **Cox A.N., Stewart J.N.** Rosseland opacity tables for population I compositions // Astrophysical J. Supplements Series. 1970. Vol. 19, No. 174.
6. **Zeldovich Ya.B., Rizer Yu.P.** Physics of shock waves and high-temperature hydrodynamic phenomenon. Moscow: Nauka, 1966.
7. **Ulmschneider P., Schmitz F., Kalkofen W., Bohn H.U.** Acoustic waves in the solar atmosphere. V. On the chromosphere temperature rise // Astronomy and Astrophysics. 1978. Vol. 70. P. 487-500.
8. **Alekseenko S.V., Dudnikova G.I. etc.** Acoustic wave heating of the solar atmosphere // Russ. J. Eng. Thermophys. 1998. Vol. 8, No.1-4. P.95-108.
9. **Priest E.R.** Solar magnetohydrodynamics. Moscow: Mir, 1985.